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TECHNICAL NOTE

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SOME BASIC CONSIDERATIONS OF TELEMETRY SYSTEM DESIGN

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SUMMARY

A basic description of some of the main factors involved in the design of a telemetry system is presented. Variations of system parameters are given in tables and graphs, and are discussed separately so that a single element of a system, such as the gain of a parabolic antenna, may be considered. Finally, illustrative examples of computations for a complete system are given.

SOME BASIC CONSIDERATIONS OF TELEMETRY SYSTEM DESIGN

INTRODUCTION

The planning and design of a communication system (as for satellite or probe data telemetry, communication via satellite relays, etc.) brings one to consider simultaneously several fundamental parameters: e.g., carrier frequency, transmitter power, transmission loss, antenna gains, receiver sensitivity, information bandwidth and rate, and so on. At least in the early planning stage of a system design it is desirable to employ a simplified procedure. In general, such a procedure involves the assumption or choice of one or more system parameters, followed by determination of the remaining system parameters — all choices and determinations, of course, being consistent with the system specification.

FREE-SPACE TRANSMISSION

The basic formula* for radio transmission in free space may be written

$$P_r/P_t = A_r A_t / d^2 \lambda^2 , \qquad (1)$$

where P_r and P_t are, respectively, the received and transmitted powers; A_r and A_t are, respectively, the effective areas of receiver and transmitter antennas; d is the distance between transmitter and receiver; and λ is the radio wavelength. P_r and P_t are in the same units of power; A_r, A_t, d, and λ all employ the same units of length. Equation (1) is valid only for

$$d \geqq 2a^2/\lambda$$

where a is the largest linear dimension of either antenna.

For computation purposes, it is convenient to consider the attenuation in decibels between two isotropic antennas. Thus in Eq. (1), setting $A_r = A_t = \lambda^2/4\pi$ (see next section) and taking the common logarithm of both sides, we obtain

$$\begin{aligned} \text{Attenuation (db)} &= 10 \log_{10} (P_r/P_t) \\ &= -20 \log_{10} d_{\text{miles}} + 20 \log_{10} \lambda_{\text{meters}} - 20 \log_{10} 4\pi \\ &\qquad - 20 \log_{10} 1609 \qquad (2) \end{aligned}$$

where d and λ have the units given by the sub-notations and the constant 1609 is the number of meters per statute mile.

Equation (2) is plotted in Fig. 1 as attenuation versus distance with wavelength as a parameter. The increase in transmission loss, at a given wavelength, is 20 db per decade of distance. Also, the transmission loss at a given distance increases 20 db per decade of frequency.

*Friis, H.T., "A Note on a Simple Transmission Formula," Proc. IRE 34(5):254, May 1946.

It should be emphasized that Eq. (2) and Fig. 1 give the attenuation (or transmission loss) between two isotropic antennas. For practical antennas, the gain referred to the isotropic antenna must be considered as given in the next section.

ANTENNA GAIN

If an antenna is immersed in a field of power density P_o, and if the power at the antenna terminals then is P_r, the effective area of the antenna can be defined as

$$A = P_r/P_o .$$

By this definition the effective area of an isotropic antenna is

$$A_{iso} = \lambda^2/4\pi .$$

Now we define antenna gain (referred to an isotropic radiator) as the ratio of its effective area to the quantity $\lambda^2/4\pi$. (Table 1 lists the effective areas and gains of some common antenna types, and Fig. 2 gives the gain as a function of diameter in the case of a circular parabolic antenna.) Now suppose one wishes to compute the net transmission loss between a half-wave antenna and a 30-foot-diameter parabola in a 300-Mc system for a distance of 40,000 miles. The computation is as follows:

Transmission loss, isotropic to isotropic (Fig. 1):	-178 db
Gain of half-wave antenna (Table 1):	+2 db
Gain of 30-foot-diameter parabola (Fig. 2):	+26 db
Net transmission loss:	-150 db

Thus, under the assumptions made, 1 watt of transmitted power would result in a received power 150 db below 1 watt; i.e., -150 dbw or -120 dbm (db below 1 milliwatt). If a -120 dbm signal is considered insufficient, the transmitter power or the gain of one or both antennas must be increased. If a -120 dbm signal is excessive, a reduction of the transmitter power or antenna gains may be considered. The actual required power at the receiver input can be determined by signal-to-noise considerations (see next section).

SIGNAL-TO-NOISE RATIO

A theoretically perfect receiver would have a noise output power corresponding to the Johnson noise in the receiver's input circuit. The Johnson noise power is given by

$$N = kTB$$

where N is the noise power in watts; k is Boltzmann's constant; T is the absolute temperature in degrees Kelvin; and B is the bandwidth in cycles per second. The perfect receiver would produce no degradation of signal-to-noise ratio, i.e., the output signal-to-noise ratio would be equal to the input signal-to-noise ratio.

Any real receiver contains one or more noise sources; thus the signal-to-noise ratio at the output is inferior to that at the input. The magnitude of this degradation is called the "noise figure" (NF) and may be computed as follows:

$$NF = 10 \log_{10} N_t - 10 \log_{10} B + 203.9$$

where N_t is the total noise power (referred to the receiver input).

The above equation is plotted in Fig. 3. This graph can be used to determine (a) the noise figure of a receiver of known bandwidth and noise power (referred to the receiver input) or (b) the required signal input power for a required signal-to-noise ratio. It is also noteworthy that the horizontal-axis intercepts (0-db noise figure) in Fig. 3 give the value of the Johnson noise power ($N = kTB$) in a given bandwidth.

As an example of the use of Fig. 3, suppose that a particular system requires a receiver bandwidth of 100 kc. A receiver having a 4-db noise figure and a 100-kc bandwidth has an equivalent input circuit noise of -120 dbm. Thus an input signal power of -120 dbm would produce an output signal-to-noise power ratio of unity, or 0 db. If a 3-db signal-to-noise ratio is required, the input signal must be -117 dbm; for a 6-db ratio, the signal must be -114 dbm; etc.

In a communications system conveying information in amplitude form, the fidelity and/or resolution of the system is a function of the signal-to-noise ratio. In a variety of practical systems the number of distinguishable amplitudes (n) may be $\sqrt{1 + S/N}$, where S/N is the signal-to-noise power ratio.* Figure 4 shows the number of amplitudes distinguishable (with almost perfect reliability) for a given S/N ratio. It may be noted that for 10/1 (10-db) S/N ratio one may reliably distinguish only 3 amplitudes.

SAMPLE PROBLEMS

Use of the material herein is illustrated by the following examples.

1. Problem: Determine the anticipated minimum signal-to-noise ratio for the following proposed system.

Satellite transmitter:	1/2 watt, 20 Mc
Satellite antenna gain:	0 db
Maximum slant range:	2000 miles
Receiver antenna gain:	8 db
Receiver sensitivity (S/N = 1):	5 microvolts
Receiver input impedance:	50 ohms

Solution:

Transmitter power:	-3 dbw
Transmitter antenna gain:	0 db
Transmission loss (Fig. 1; 2000 mi, 20 Mc):	-126 db
Receiver antenna gain	8 db
Receiver input power:	-121 dbw

The receiver input power (-121 dbw) corresponds to 8×10^{-13} watt; this power in the 50-ohm input circuit will produce about 6.3 microvolts. Hence,

$$S/N\big|_{min} = 6.3/5 \approx 1.3/1 \ .$$

2. Problem: Design a radio telemetering system with a 500-kc information bandwidth, for use in a 1000-mile-range vertical probe, and to provide a minimum signal-to-noise ratio of unity.

Solution: Here most system parameters have been left to the designer's choosing. One might proceed as follows:

*Hershberger, W.D., "Principles of Communication Systems," p. 45, New York:Prentice-Hall, 1955.

(1) Assume a double-sideband amplitude-modulation system and, hence, a receiver bandwidth of 1 Mc. To accommodate this bandwidth easily, assume the carrier frequency to be at least 100 Mc.

(2) Assume (conservatively) that a receiver with a 10-db noise figure is available for any frequency from 100 to 3000 Mc. Figure 3 shows that the input-circuit noise power of a 10-db 1-Mc-bandwidth receiver is -134 dbw. This, then, is the required receiver input level for a signal-to-noise ratio of unity.

(3) From Fig. 1 it is found that the transmission loss for 1000 miles (between two isotropic antennas) is -136 db at 100 Mc and -166 db at 3000 Mc. Thus, considering the -134 dbw required receiver input, a factor of 2 db at 100 Mc is required whereas the corresponding 3000-Mc factor is 32 db. The items remaining to be considered are antennas and transmitter power.

(4) Since it is usually desirable to use lightweight low-power-drain probe equipment, assume a 0-db gain for the transmitting antenna.

(5) Now a few of the infinity of possible systems may be set down as follows:

Frequency	Transmitter Power	Receiver Antenna Gain
100 Mc	-3 dbw (1/2 watt)	5 db
100 Mc	-10 dbw (1/10 watt)	12 db
300 Mc	0 dbw (1 watt)	12 db
1000 Mc	0 dbw (1 watt)	22 db
3000 Mc	0 dbw (1 watt)	32 db

The final choice may now be made on any of several logical considerations (e.g., frequency allocations, available antennas, etc.), but from the standpoint of overall system simplicity one leans toward the 100-Mc choice. So, finally, the following system could be proposed.

Frequency:	100 Mc
Modulation:	Double-sideband AM
Receiver bandwidth:	1 Mc
Receiver noise figure:	10 db
Receiver input for S/N = 1:	-134 dbw
Transmitter power (1/10 watt):	-10 dbw
Transmitter antenna gain:	0 db
Transmission loss (for 1000 miles):	-136 db
Receiving antenna gain (5-element array):	12 db
Receiver input power:	-134 dbw

3. Problem: Same as Problem 2 except that, in addition, a 225-Mc 1-watt transmitter is to be used.

Solution: With the additional transmitter specification there remains only the receiving antenna to specify.

Transmitter power (1 watt):	0 dbw
Transmitter antenna gain:	0 db
Transmission loss:	-142 db
Minus required receiver input:	134 dbw
Deficiency:	-8 db

Hence a receiving antenna gain of 8 db is required; this can be obtained by a 2-element broadside array or by a helical antenna of modest size.

4. Problem: Determine the number of distinguishable amplitudes that could, with high reliability, be conveyed by the following system:

Frequency:	100 Mc
Transmitter power:	1 watt
Transmitter antenna:	isotropic
Distance:	500 miles
Receiver bandwidth:	30 kc
Receiver noise figure:	3 db
Receiver antenna gain:	14 db

Solution:

Transmitter power (1 watt):	0 dbw
Transmitter antenna gain:	0 db
Transmission loss (Fig. 1):	-130 db
Receiver antenna gain:	14 db
Receiver input power:	-116 dbw

The input noise power for a 3-db, 30-kc bandwidth receiver (Fig. 3) is -156 dbw. Hence the signal is 40 db (156 - 116) above the noise, and S/N = 10,000/1. The number of distinguishable levels is therefore

$$\sqrt{1 + S/N} = \sqrt{1 + 10{,}000} \approx 100.$$

5. Problem: Determine the transmitter power required to produce a 10/1 signal-to-noise ratio in a 10-kc-bandwidth 400-Mc receiver with a 10-db noise figure, using a 0-db receiving antenna and a 250-foot-diameter parabola for transmitting. The transmitter is earth-based and the receiver is in the vicinity of Venus, approximately 70 million miles away.

Solution: From Fig. 3 we find that a 10-db 10-kc receiver has a noise level of -154 dbw; if S/N = 10/1 = 10 db, the required receiver input is -154 + 10 = -144 dbw. Then

Transmitter antenna gain (Fig. 2):	47 db
Transmission loss (Fig. 1):	-244 db
Receiver antenna gain:	0 db
Minus required receiver input:	144 dbw
Deficiency:	-53 dbw

Thus the transmitter power must be 53 dbw or 200 kilowatts.

SAFETY FACTORS

The design of any real, operational telemetry system should of course include some margin of safety, or allowance for deterioration. Exactly where to insert such allowance in a system is a matter of decision based on cost, feasibility, etc. In any event, before "wrapping up" a design, the system designer must consider some or all of the following items and make appropriate allowance therefor.

1. Non-free-space transmission conditions. At the lower frequencies, ionospheric absorption, refraction, and reflection occur. At higher frequencies, atmospheric effects become important.

2. Noise. Both man-made and natural sources may contribute to the total receiver input noise. Some bad offenders in the man-made category are electrical machinery, leaky electrical distribution systems, automobile ignition systems, and radars. Natural sources of noise include lightning discharges and the variety of extraterrestrial sources.

3. Antenna anisotropy. Received or transmitted power may be seriously reduced by antenna anisotropies. For example, roll or spin of an anisotropic radiating system produces amplitude fluctuations at the input of a remote receiver. Similarly, directional antennas are useful only if properly trained; thus, particularly for high-gain arrays, one may well consider allowing for antenna-train errors.

4. System deterioration. The combined effects of component aging, environment, and operational error can seriously degrade the performance of a system. Here one tries to predict the "db-loss" expected owing to factors such as battery-voltage decline, changes in crystal-controlled frequencies, detuned receiver circuits, increased transmission-line losses, etc.

5. Velocity effects. The apparent frequency received from a moving transmitter differs from the actual transmitted frequency by the Doppler shift. To accommodate this shift may require a bandwidth greater than that required by the modulation alone. In any event, the receiver must be designed to accept the Doppler-shifted frequencies.

Another effect of transmitter velocity relative to the receiver is the apparent forward-beaming of the power radiated from a source moving at an appreciable fraction of the speed of light. If, for example, a transmitter were receding from a receiver at a speed 0.2 that of light, the received power would be less than 60 percent of the power received from a stationary transmitter. Whereas near-relativistic transmitter-velocities are not a reality today, tomorrow the attendant problems must be faced.

CONCLUSION

Telemetry system design or planning, being by nature a somewhat disordered process of selection of interrelated parameters, is best attacked by the most orderly approach one can devise. It is hoped and felt that the material assembled here can provide some aid to those who wish to examine, in whole or in part, telemetry systems.

Table 1
Effective Areas and Gains of Antenna Types

Antenna Type	Effective Area	Gain (referred to isotropic antenna)	
		Ratio	db
Isotropic	$\lambda^2/4\pi$	1	0.00
Dipole*	$3\lambda^2/8\pi$	1.5	1.76
Half-wave	$0.1305\ \lambda^2$	1.64	2.15
Broadside array† (n elements)	$n\lambda^2/4$	$n\pi$	8.0 (n = 2) 9.7 (n = 3) 11.0 (n = 4) 12.0 (n = 5) 12.8 (n = 6) 13.4 (n = 7) 14.0 (n = 8) 14.5 (n = 9) 15.0 (n = 10)
Circular parabolic reflector‡ (diameter d)	$0.5\,\pi d^2/4$	$0.5\,(\pi d/\lambda)^2$ (see Fig. 2); d and λ in same units.	

*Uniform-current element. Length very short compared to a wavelength.
†Rows of half-wave dipoles spaced half a wavelength apart. Current in all dipoles of equal amplitude and phase. With a reflector.
‡Assume 50 percent aperture efficiency.

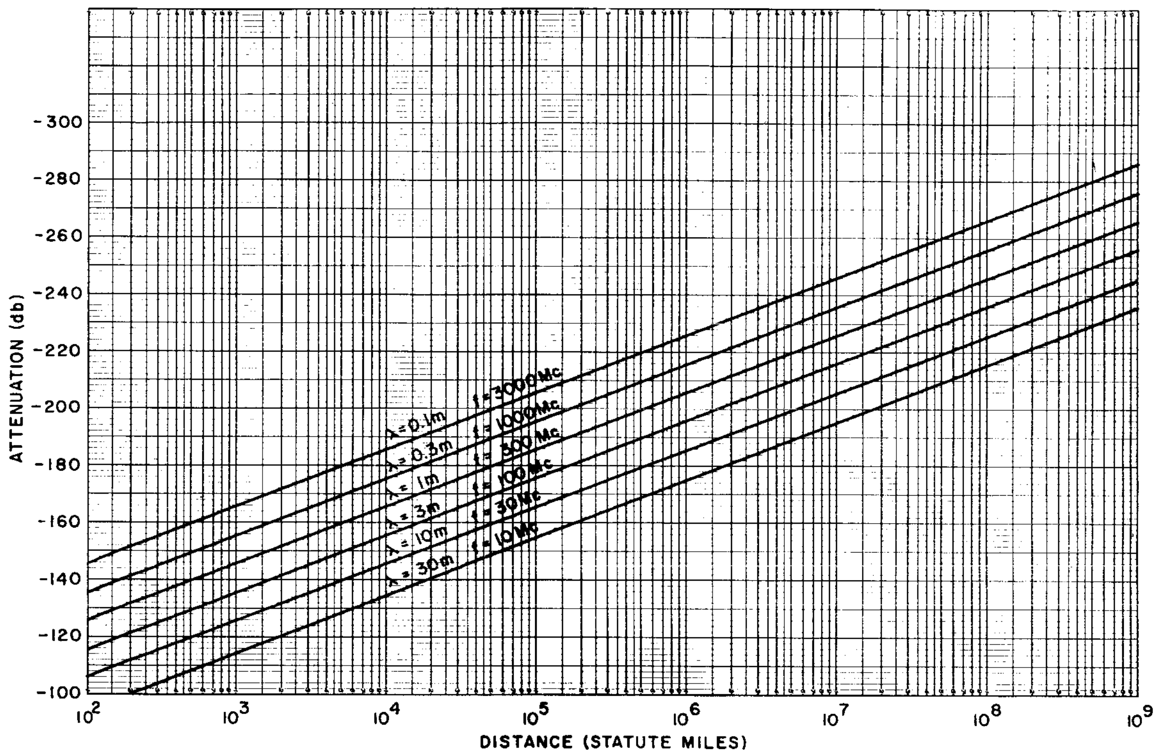

Fig. 1 - Attenuation as a function of distance between isotropic antennas in free space

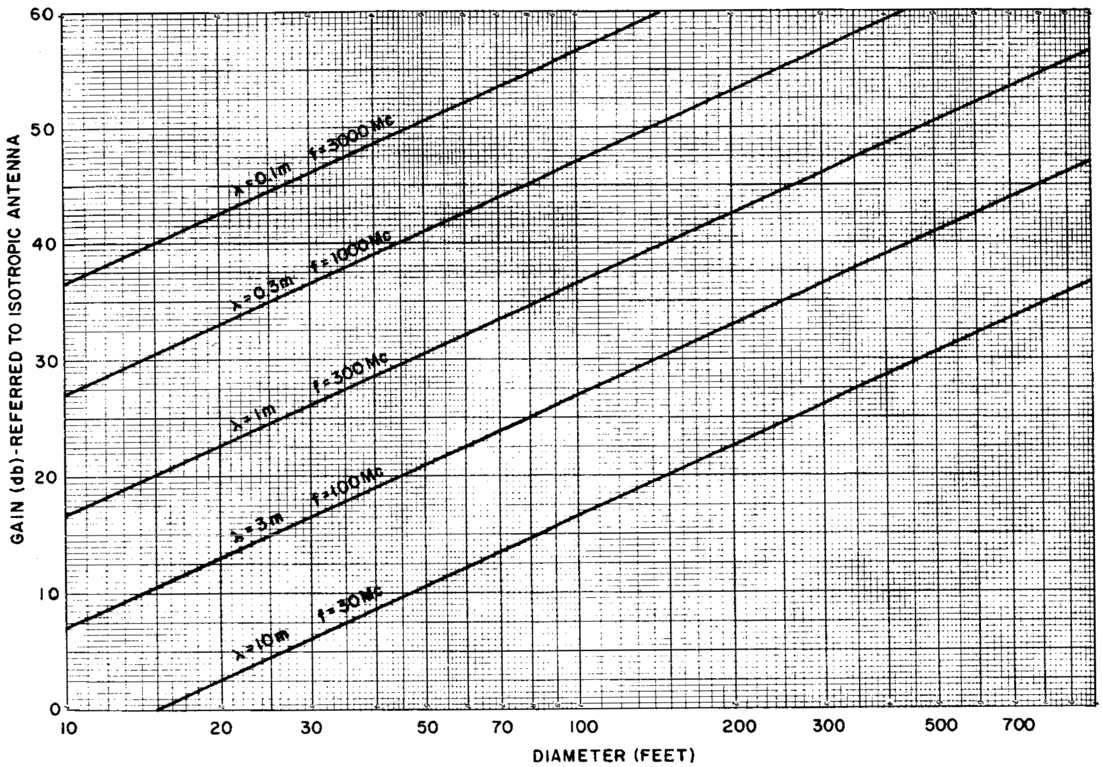

Fig. 2 - Gain of a circular parabolic antenna as a function of diameter (assumed aperture efficiency: 50%)

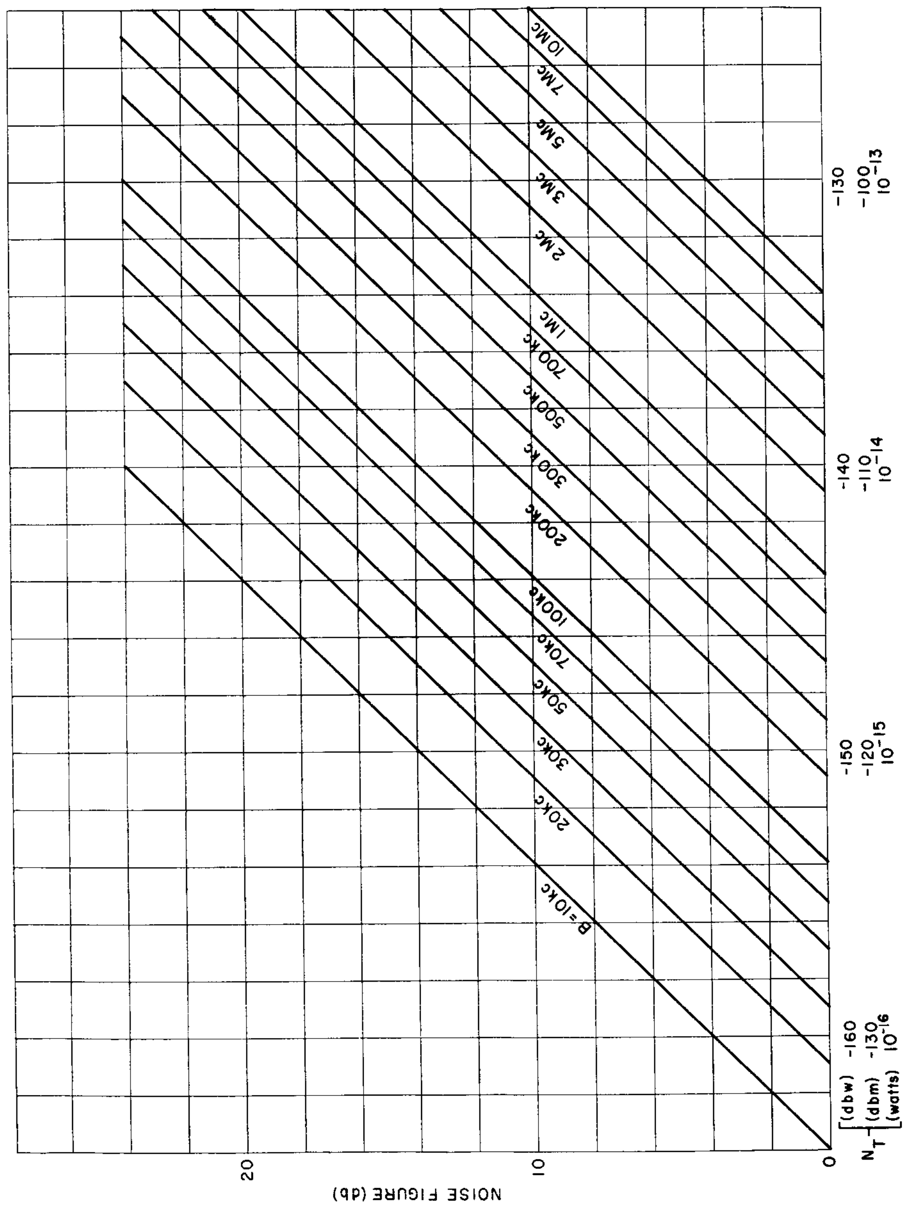

Fig. 3 - Receiver noise figure as a function of noise power

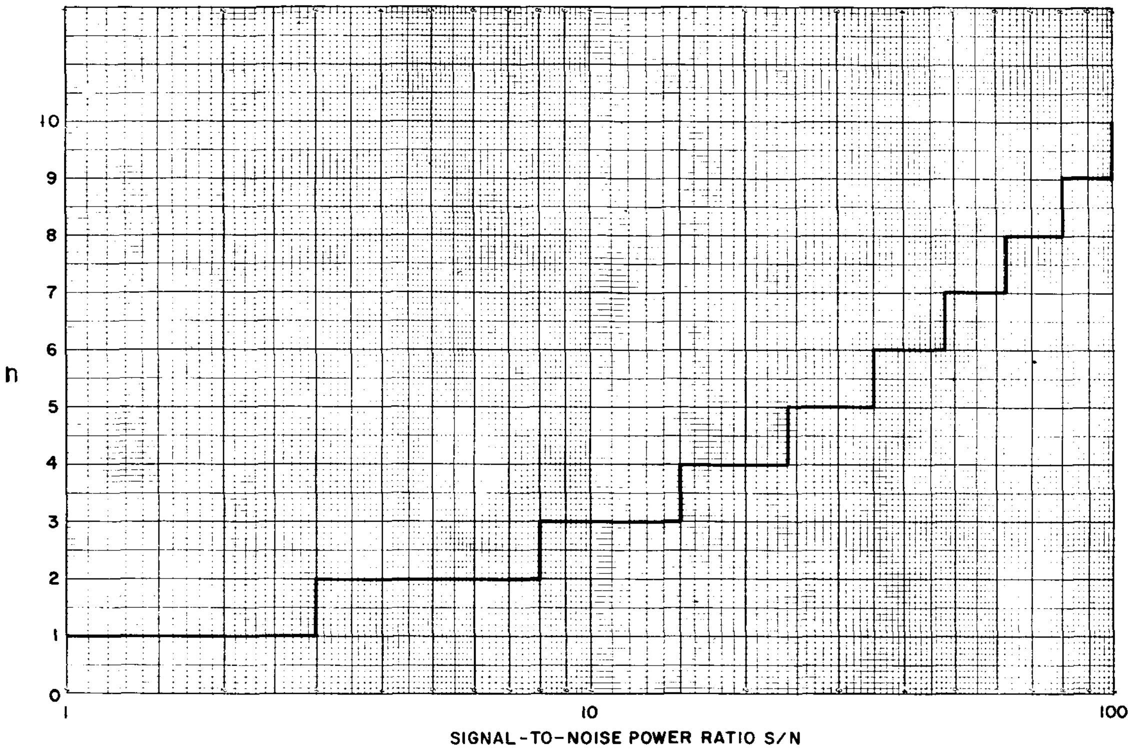

Fig. 4 - Number of distinguishable amplitudes (n) as a function of signal-to-noise power ratio (S/N)

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